Synoptic Analysis of Episodic Easterly Wind Events in Central-Western North Dakota for the Years 2000 – 2002

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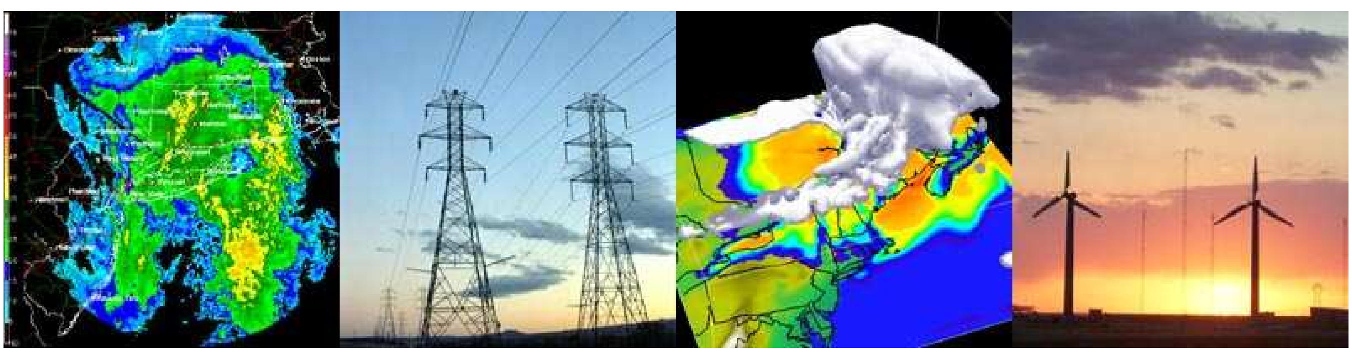

Synoptic Analysis of Episodic Easterly Wind Events in Central-Western North Dakota for the Years 2000 – 2002

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Abstract

A synoptic meteorological analysis has been completed for one primary and four secondary periods suspected of having significant duration easterly wind events in the years 2000-2002 for central and western North Dakota. The analyses utilize RUC and NARR archived weather data for reconstruction of the synoptic meteorological fields to identify periods of prolonged easterly flow and to describe the large-scale forcing responsible in the low-level flow regime.

1. Introduction

Five periods during the years 2000-2002 were identified by the North Dakota Department of Health that were suspected of containing considerable duration easterly wind episodes that could transport effluents westward from central North Dakota. The primary evaluation period spanned the dates of 22 August 2002 – 12 September 2002, with secondary analysis periods identified in February of 2000 and 2001, December of 2000, and March of 2002. The meteorological approach involved reconstructing the synoptic situation in each of these evaluation periods using data archived from the analysis fields of the National Center for Environmental Prediction's (NCEP) Rapid Update Cycle (RUC) model and from the NCEP North American Regional Reanalysis (NARR) archive. The data were visualized in WindLogics Environmental Workbench™ (EWB) software to assess the large-scale meteorological influences on the regional flow regime of central and western North Dakota.

2. Data Source Characteristics

The primary data source for these synoptic case evaluations is the WindLogics RUC analysis archive. The RUC model (Benjamin et al. 2004) is unique among the NCEP models in that analyses are produced every hour, versus every six hours for the other models used for longer term forecasting. The RUC uses a process known as continuous assimilation, in which short, one hour forecast segments are interspersed with applications of the data assimilation process. This means that each hour, the one-hour forecast fields are corrected, based on the real-time data collected by the numerous observational platforms controlled by National Oceanic and Atmospheric Administration. The model is never allowed to stray too far from the actual state of the atmosphere, within limits determined by observational sampling frequency, density, and accuracy. Frontal positions, for instance, can be reasonably well adjusted for in the assimilation process. The horizontal grid resolution of the archived RUC analysis data is 40 km for the years 2000 – 2002; however, for February 2001, 80 km resolution RUC analysis data was used to fill a gap in the standard 40 km RUC archive. For most of the second half of August of 2002, where a gap exists in the RUC archives, the NARR dataset has been utilized. This reanalysis dataset has 32 km horizontal grid resolution and is based on the NCEP ETA model. Advanced data assimilation techniques have been utilized in the NARR project. Details on the NARR dataset may be found in Mesinger et al. (2003) and at the NCEP NARR website http://wwwt.emc.ncep.noaa.gov/mmb/rreanl.

3. Synoptic Animations

Three animations have been created to support the synoptic analysis for the primary evaluation period. The first animation provides information on the surface pressure distribution and 10 m vector winds. The second and third animations provide the geopotential height distribution and vector winds at the 900 mb and 250 mb pressure levels. The selection of these three levels allows for the identification and analysis of synoptic regimes favoring episodes of low-level easterly flow over central and western North Dakota, while also addressing the jet stream configuration and substructure (jet streaks) that are dynamically related to the low-level pressure system configuration. The animations are composed of frames with a 3 hour time increment up to 30 August 2002 and a 1 hour time increment thereafter. The difference in the hours between frames exists because the animations are composed of both NARR and RUC data. NARR data is available every 3 hours while RUC data is available every hour. The frame rate of all animations is 1 frame per second.

4. Synoptic Analysis

Primary Evaluation Period: 22 August – 12 September 2002

The examination of the primary evaluation period has revealed 1 extended span with either easterly low-level winds or winds with a significant easterly component. Four other episodes with easterly flow (or flow having a significant easterly component) capable of boundary layer effluent transfer of at least about 150 km were also identified. Given that the emphasis of this investigation is for synoptic evaluation of easterly wind events, a trajectory model was not run on the boundary layer flow and this estimate of east to west parcel movement was quite approximate.

<u>Event 1</u>

Although the beginning of the specified evaluation period was 22 August, an examination of the low-level flow regime indicated that the longest duration easterly flow regime actually started at about 18 UTC (Coordinated Universal Time, 12 CST) on 20 August. This extended period with a marked easterly wind component lasted until approximately 15 UTC on 22 August. The surface pressure and wind (10 m) analysis shown in Figure 1 displays the conditions early in this episode. Also shown in Figure 1 is the 900 mb flow field that provides insight into the low-level flow approximately 200 – 600 m above the surface in central and western North Dakota (height range is due largely to the elevation gradient). As indicated in the figure, the low-level flow in the western half of North Dakota is dominated by southeasterly and easterly flow around a modest low pressure system ("cyclone" will also be used synonymously with low pressure system) centered near the Black Hills region of South Dakota. This slow moving cyclone weakened as it moved east into eastern South Dakota; however, a broad region of low pressure remained across South Dakota and Nebraska through approximately 00 UTC on 22 August. This persistent low pressure in conjunction with the increasing influence of a southwest-northeast axis of high pressure (evident from north central North Dakota into southern Manitoba) served to provide a sufficient south-north pressure gradient across North Dakota to maintain low-level flow with a significant easterly component. As would be expected, the 900 mb flow in Figure 1 shows increased wind speeds (~5-8 m s^{-1}) relative to the 10 m level and a slightly veered directional profile consistent with Ekman turning in the boundary layer and with regions of warm air advection east and northeast of low-pressure systems.

As shown in Figure 2, the latter part of this easterly wind episode is most influenced by the anticyclonic wind regime of the aforementioned high pressure region (anticyclone) to the north. Since the time of the Figure 2 analysis is 09 UTC (03 CST) on 22 August, nocturnal boundary layer influences have diminished near-surface wind speed. However, at 900 mb, the anticyclonic flow field is quite evident and the east-southeast winds exceed 10 m s^{-1} over much of central and western North Dakota. This extended event eventually subsides as the predominant wind direction turns more southerly and the synoptic pressure gradient over the region relaxes.

To understand the driving mechanisms for the distribution and intensity of low-level pressure systems, several levels of the mid-upper troposphere were examined. The surface cyclone represents a pressure minimum within a much larger region of reduced surface pressure corresponding to a lee-side trough initially running from southeast Montana to northeast Colorado. This lee-side trough (i.e., downslope region east of the Rockies) has formed in response to the advection of a strong lower-tropospheric thermal ridge ahead of a large amplitude upper-level trough over the western United States. The large amplitude trough was evident in the upper-level analysis from 700 mb to near the tropopause (see the 250 mb analysis in Figure 3). Additionally, the lee-side trough is supported by downslope warming in the lee of the Front Range of the Rockies that is associated with the onset of southwesterly upper-level flow (~700 mb level). The slow eastward propagation of the large amplitude trough maintained a broad region of low pressure over the central High Plains and Great Plains downstream of the upper-level trough axis throughout this episode. The surface high pressure system that exerts a dominating influence over the low-level wind field after about 12 UTC on 21 August is the result of surface anticyclogenesis resulting from a convergent confluence region in the jet stream pattern over southeastern Saskatchewan and southern Manitoba shown in Figure 3.

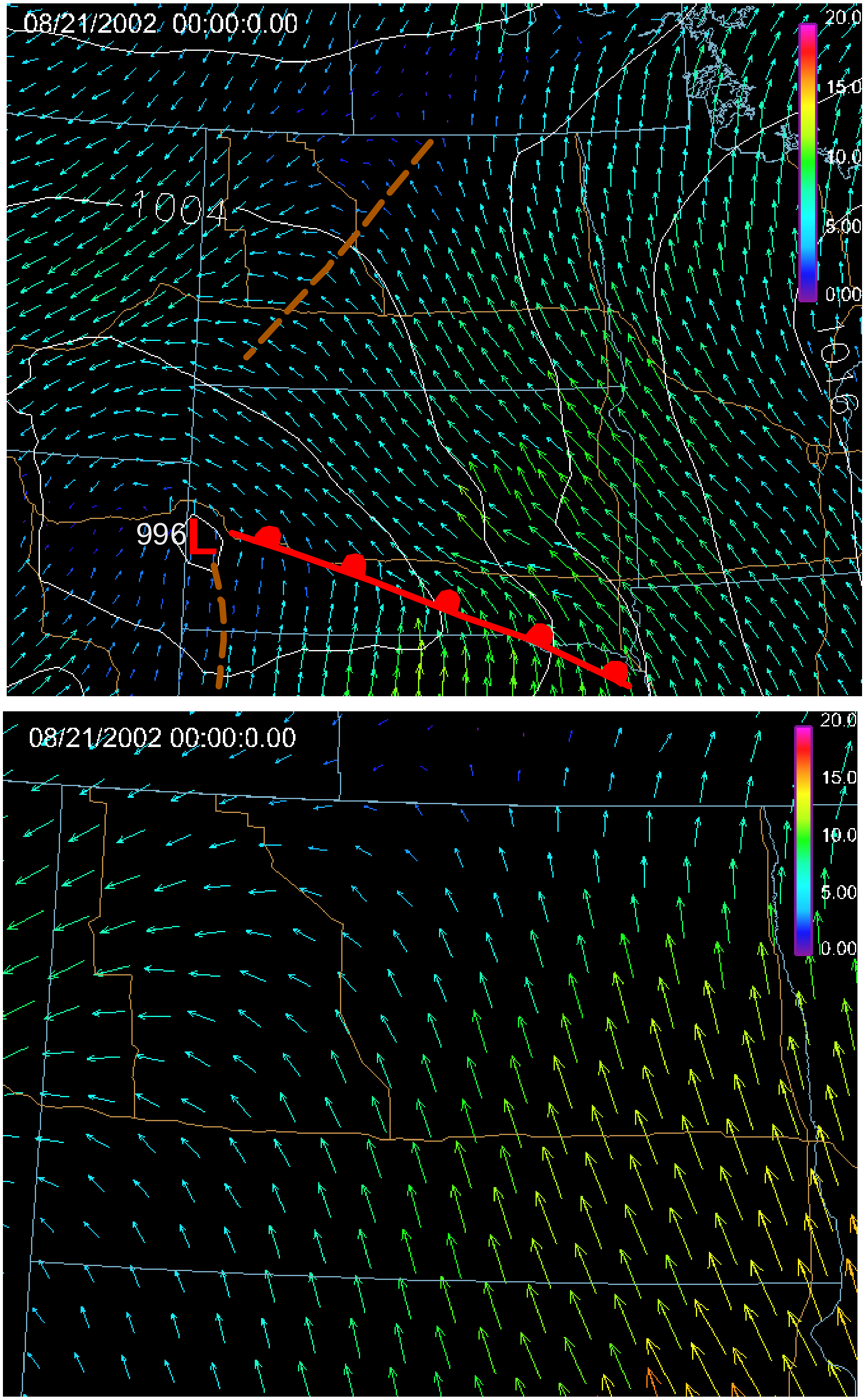

Figure 1. Surface pressure (mb) and vector winds at 00 UTC on 21 August 2002 (top panel) and 900 mb winds (bottom panel). Color bar shows vector wind magnitude in m s^{-1}.

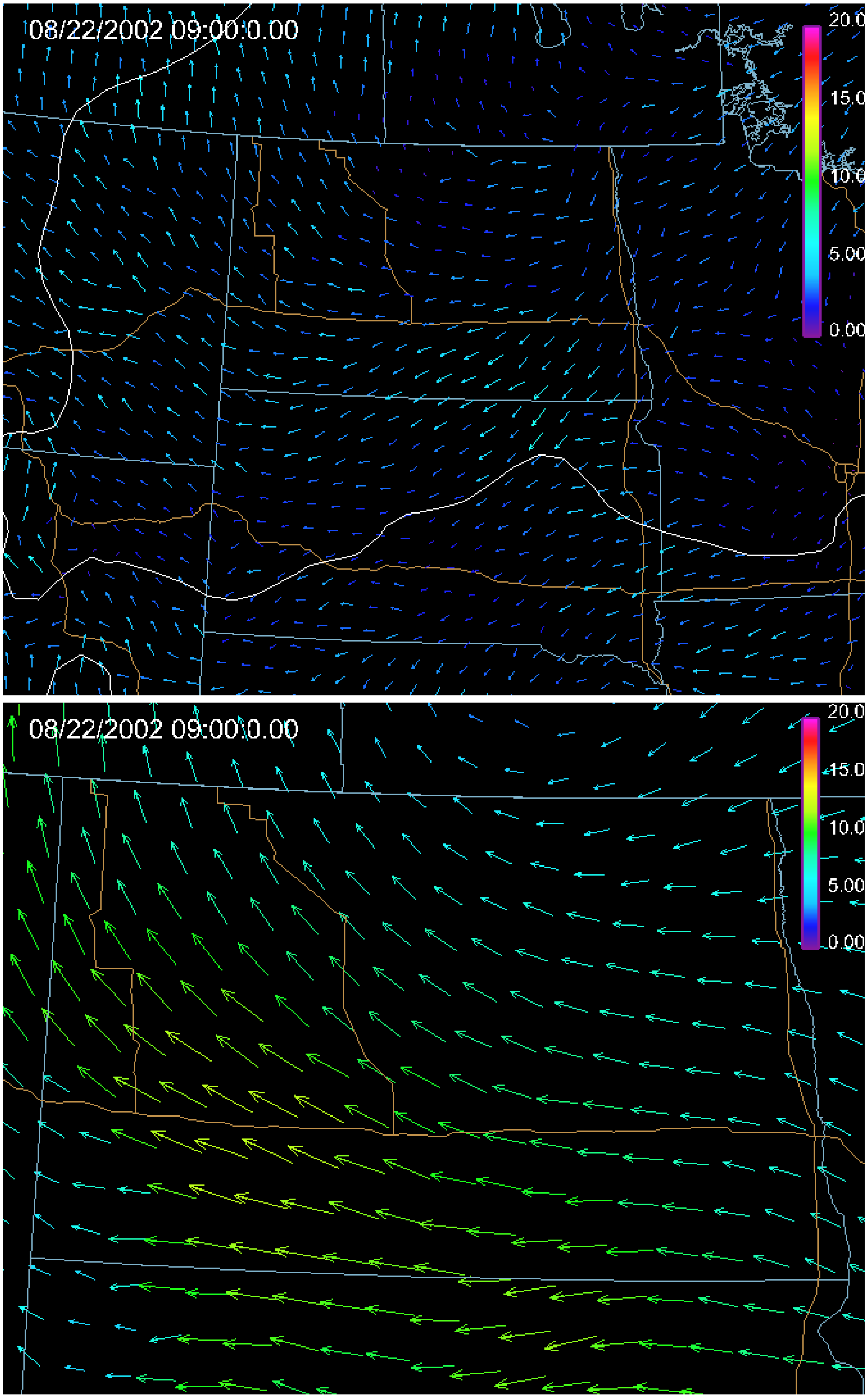

Figure 2. As in Figure 1 except at 09 UTC on 22 August 2002.

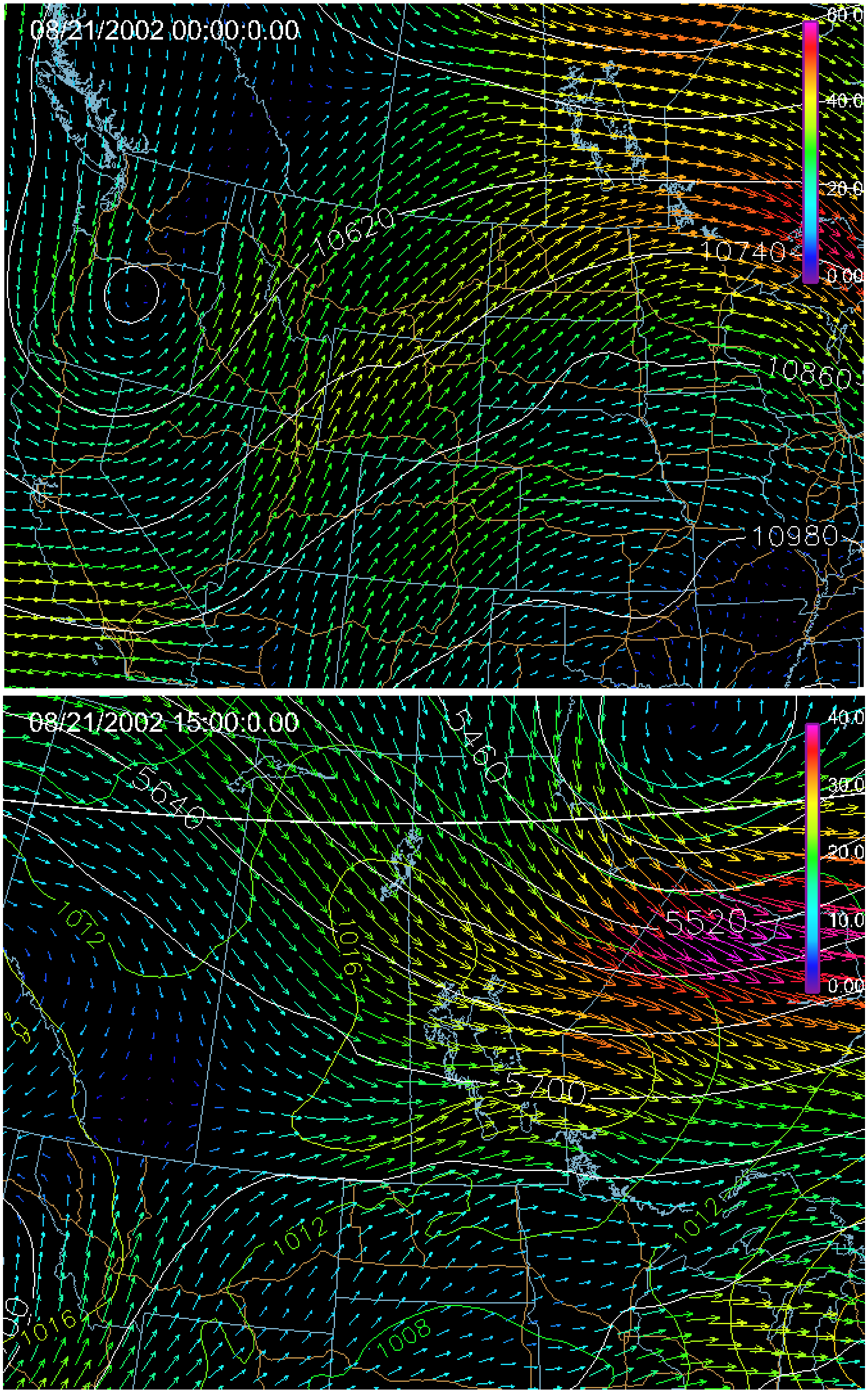

Figure 3. Geopotential height (m) and vector winds at 250 mb at 00 UTC on 21 August 2002 top panel. Same fields for 500 mb at 15 UTC on 21 August with additional surface pressure analysis (mb, colored lines) bottom panel. Color bar shows wind magnitude in m s^{-1}.

Event 2

The second significant bout of easterly winds occurred between 18 UTC (12 CST) on 5 September and 10 UTC on 6 September. This event followed a minor 6 hour episode of weak easterly flow that ended at 00 UTC on September 5 that was associated with a fast moving and weak low pressure system passing along the North Dakota - South Dakota border. In a manner very similar to the first episode of easterly winds, a surface low forms as a pressure minimum within a much broader area of reduced pressure associated with a lee-side trough extending from southeast Montana to western Nebraska as shown in Figure 4. This slow-moving low moves from its genesis region in southeastern Montana over Bismarck and into eastern North Dakota before dissipating. On this trajectory, areas along and north of the low's associated warm front (established near the North Dakota/South Dakota border for much of this event – see Figure 4) were largely in easterly flow. The 900 mb wind field shown in Figure 4 depicts the higher wind speeds expected at this level. In the heart of this episode, 900 mb winds were commonly in the 10-12 m s^{-1} range over a large portion of central and western North Dakota. These 900 mb winds showed modest veering with height relative to the surface winds as would be expected in a warm air advection layer east of the surface low position and with Ekman turning in the boundary layer. This event quickly ended with the low passing east of the region of interest and winds turning to a northerly direction.

If just the 900 mb flow is considered, this event was approximately 8 hours longer, starting at about 14 UTC on 5 September and ending at 14 UTC on 6 September. In the period between 14 UTC and 18 UTC on 5 September, surface winds were either northerly or nearly calm over much of central and western North Dakota; however, during this same period the 900 mb flow showed a significant easterly component. In the first few hours of this 4 hour period, the surface to 900 mb wind profile indicated marked veering with height. After the surface flow became nearly calm, the 900 mb flow weakened but remained in the 2.5 – 5 m s^{-1} range over much of central and western North Dakota. At the end of this event, in the period from 10 UTC to 14 UTC on 6 September, surface winds turned northerly, while concurrently, the 900 mb flow in the northern half of western and central North Dakota maintained a marked easterly component. This latter 4 hour period demonstrated the marked directional wind shear that can exist at low-levels in some instances (in this case, almost 90 degrees of veering between the surface and 900 mb over large portions of western and central North Dakota).

As in Event 1, the advection of a lower tropospheric thermal ridge and downslope warming are responsible for the broad region of lower pressure seen in Figure 4. The downslope warming is due to the southwesterly flow regime at upper-levels that is associated with the a very slow moving large amplitude trough over the western United States (Figure 5) with the trough axis still off the West Coast at 02 UTC on 6 September. Low pressure development is focused in this case by a minor jet streak passing through Wyoming during the period as is indicated in the modest wind speed increase through central and eastern Wyoming in Figure 5. Weakening of this minor jet streak resulted in the gradual demise of the surface cyclone at about 00 UTC on 7 September.

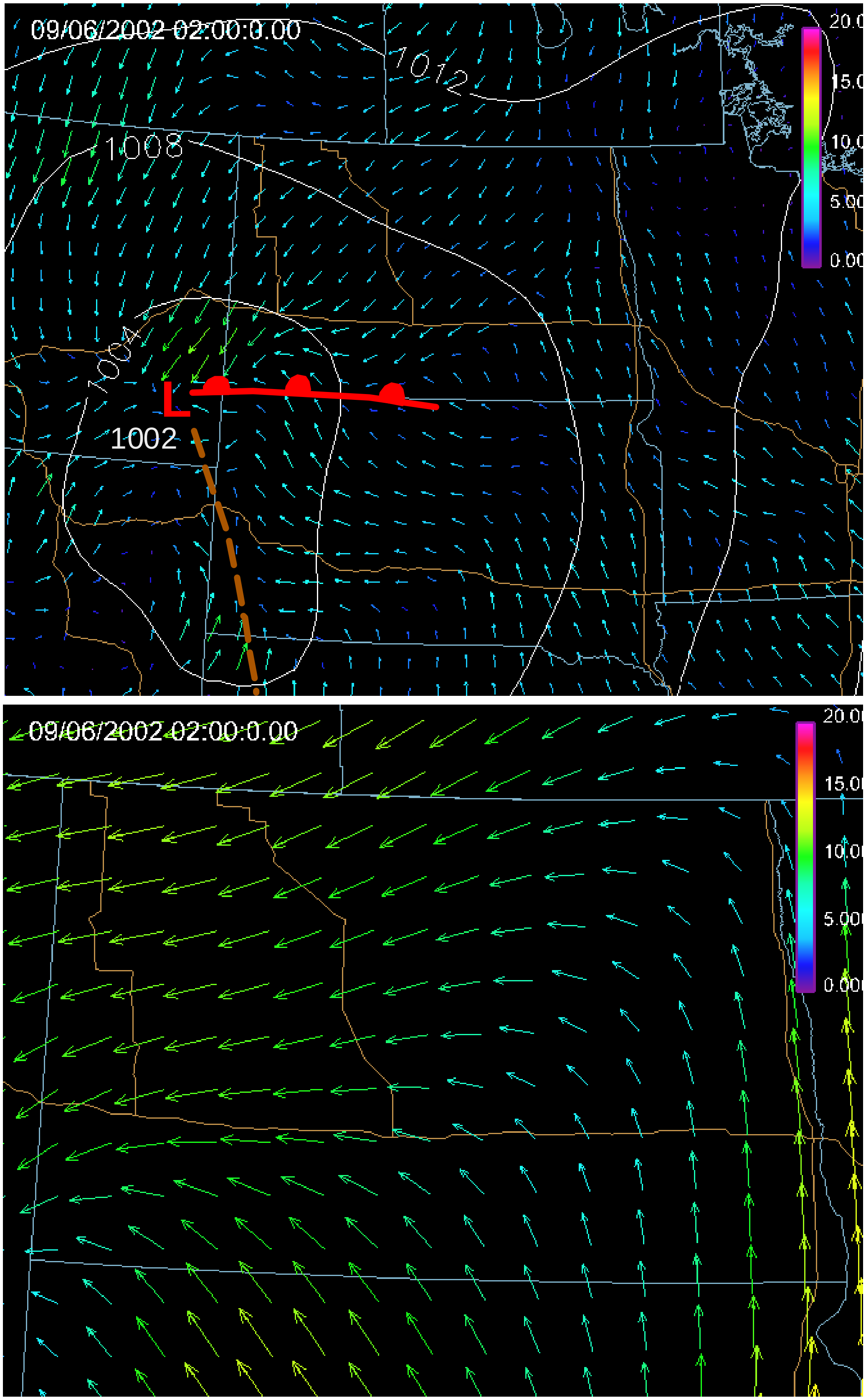

Figure 4. As in Figure 1 except at 02 UTC on 6 September 2002.

Event 3

The third easterly wind event within the primary evaluation period was of modest duration (7 hours) but had the capability of transporting effluent in the boundary layer approximately 150 km. This event spanned the period between 06 UTC (00 CST) and 13 UTC on 7 September and was associated with a low pressure system that was related to the same long wave trough discussed in Event 2 (Fig 5). As may be seen in Figure 6, a weak cyclone was located in northwest South Dakota with an attendant warm front aligned along the North Dakota - South Dakota border. A secondary circulation center may be seen in southeast Montana that had the effect of broadening the west-east extent of the low pressure region. Areas north of the warm front and low pressure region experienced easterly low-level winds until the warm front or cyclone passed over and to the north. The surface low passed just northwest of Bismarck as it moved in a northeastward direction along a lower-tropospheric baroclinic zone that was oriented parallel to the upper-level flow. As shown in Figure 6, the 900 mb easterly flow was between approximately 7-10 m s^{-1} over a large portion of the western 40 percent of North Dakota through the middle of this event. The divergent right entrance region of a mid-level jet streak appears to be dynamically responsible for this cyclone.

Considering just the 900 mb flow, this event was about 1 hour longer (ending at approximately 14 UTC on 7 September) with 900 mb east-southeast - southeast winds in the 5-10 m s^{-1} range over much of central and western North Dakota at a time when the surface winds had become very weak. In general, the last several hours of this event displayed modest directional shear (veering) and marked speed shear between the surface and 900 mb over central and western North Dakota.

Event 4

The fourth and last significant episode of easterlies over central and western North Dakota in the primary analysis period occurred between 16 UTC (10 CST) on 12 September and 04 UTC on 13 September. The easterly winds in this event were largely the result of the flow around the southern periphery of a surface anticyclone centered in southeastern Saskatchewan and southwestern Manitoba, and flow around a very weak surface trough oriented in a west-east direction along the North Dakota - South Dakota border (Figure 7). A stationary front is also located along the North Dakota/South Dakota border with the near surface flow showing a significant easterly component north of this front, although relatively weak (3 – 5 m s^{-1}). The winds at the 900 mb level over a larger portion of the western half of North Dakota were largely easterly with speeds in the 4 - 7 m s^{-1} range (Figure 7).

Similar to Event 3, when considering just the 900 mb flow, this event was about 1 hour longer (ending at about 05 UTC on 13 September), with 900 mb southeast winds in the 6-12 m s^{-1} range over much of central and western North Dakota at a time when the surface winds had become very week. In general, the latter half of this event displayed modest directional shear (veering) and strong speed shear between the surface and 900 mb over central and western North Dakota.

The most compelling dynamical explanation for the weak surface trough involves lowering of the surface pressure due to divergence aloft. This upper-level divergence is associated with the right entrance region of a modest jet streak (south of the main axis of the polar jet stream) that

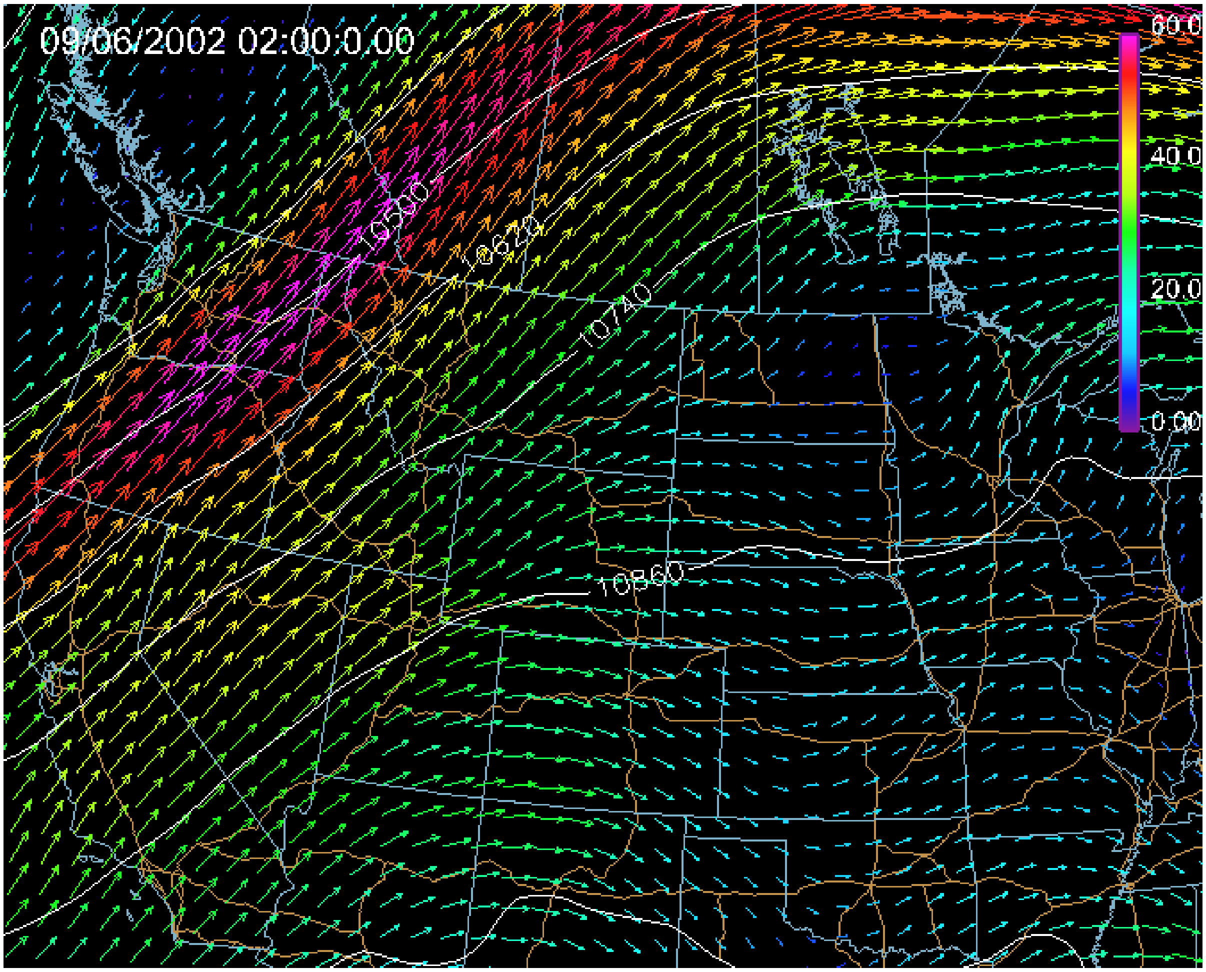

Figure 5. Geopotential height (m) and vector winds at 250 mb at 02 UTC on 6 September 2002.

can be seen along an axis from southeastern North Dakota to northeast Illinois in Figure 8. The surface anticyclone formed beneath the right exit region of a strong jet streak embedded within a northwest-southeast oriented portion of the polar jet stream as seen in Figure 8 (see leading portion of the jet streak over Saskatchewan, Manitoba and far western Ontario). Mass convergence in this quadrant of the jet streak leads to high pressure development (weak in this case) at low levels and subsiding flow through the vertical column.

Secondary Evaluation Periods

A less intensive investigation of the synoptic conditions associated with four evaluation periods in the years 2000, 2001 and 2002 was completed. As was found for the primary evaluation period, some of these intervals were comprised of multiple easterly wind episodes. In contrast, the December 2000 evaluation period only featured 2 marginal southeast wind episodes. The same evaluation criteria were used to identify easterly wind events as was utilized for the primary evaluation period.

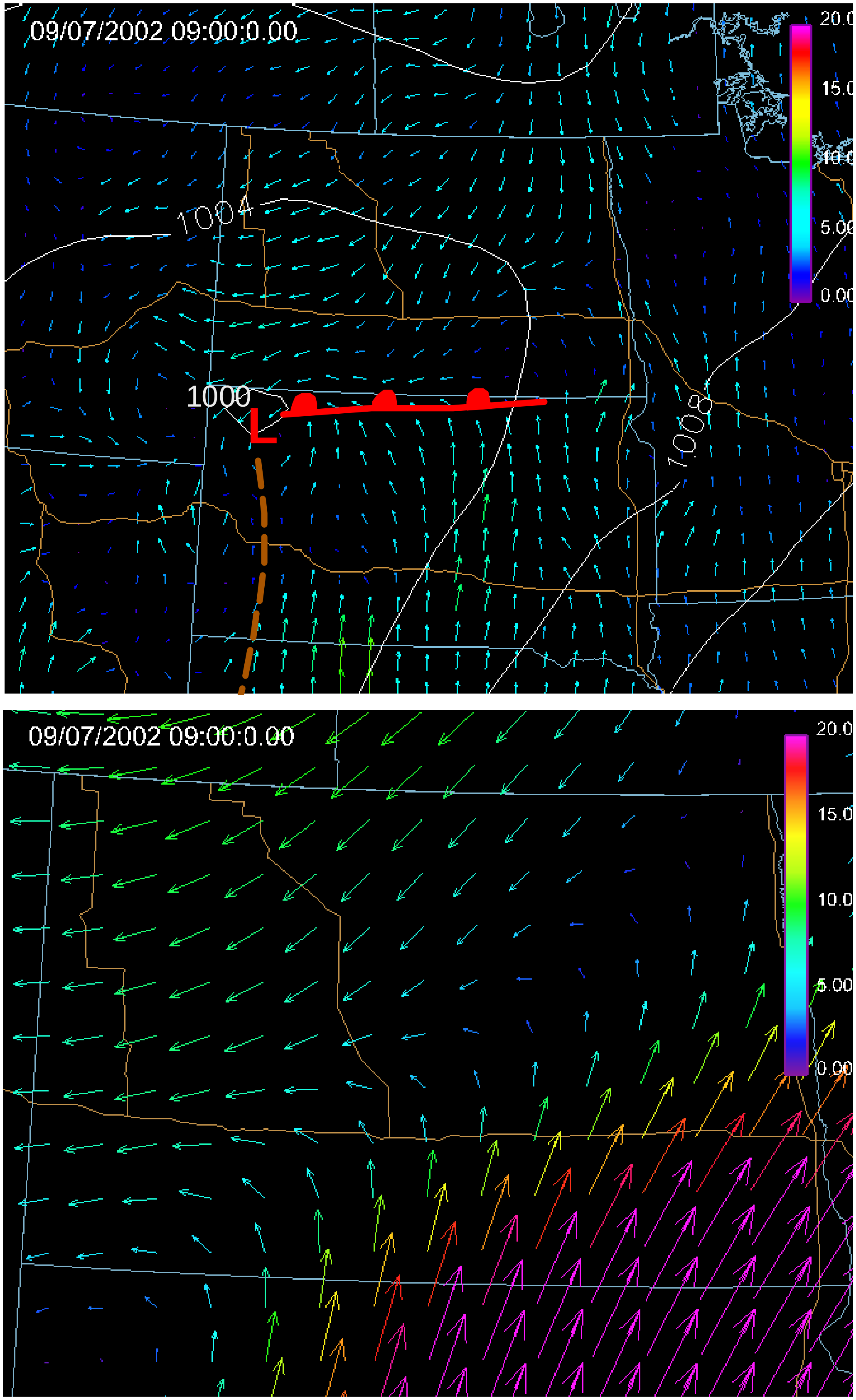

Figure 6. As in Figure 1 except at 09 UTC on 7 September 2002.

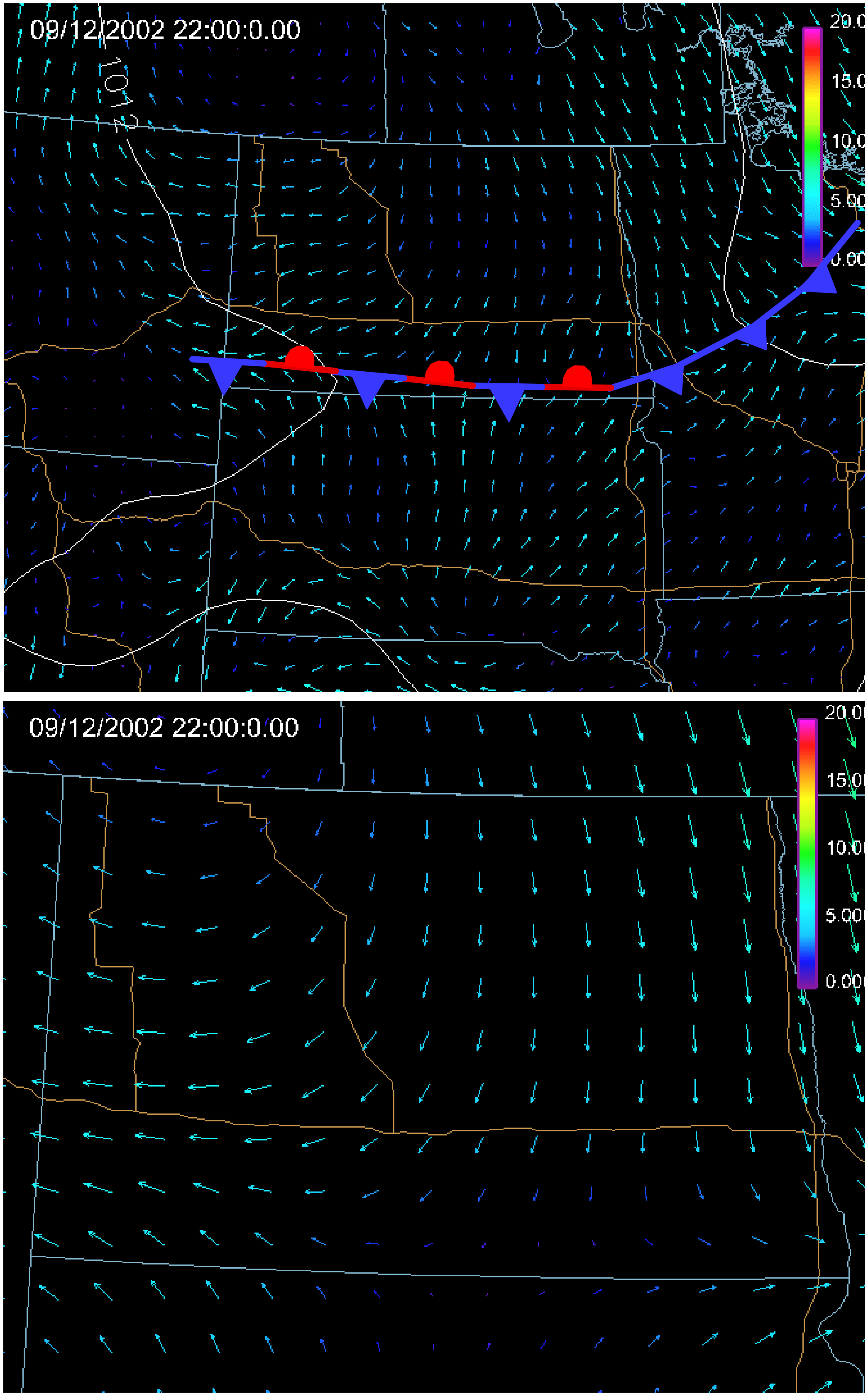

Figure 7. As in Figure 1 except at 22 UTC on 12 September 2002.

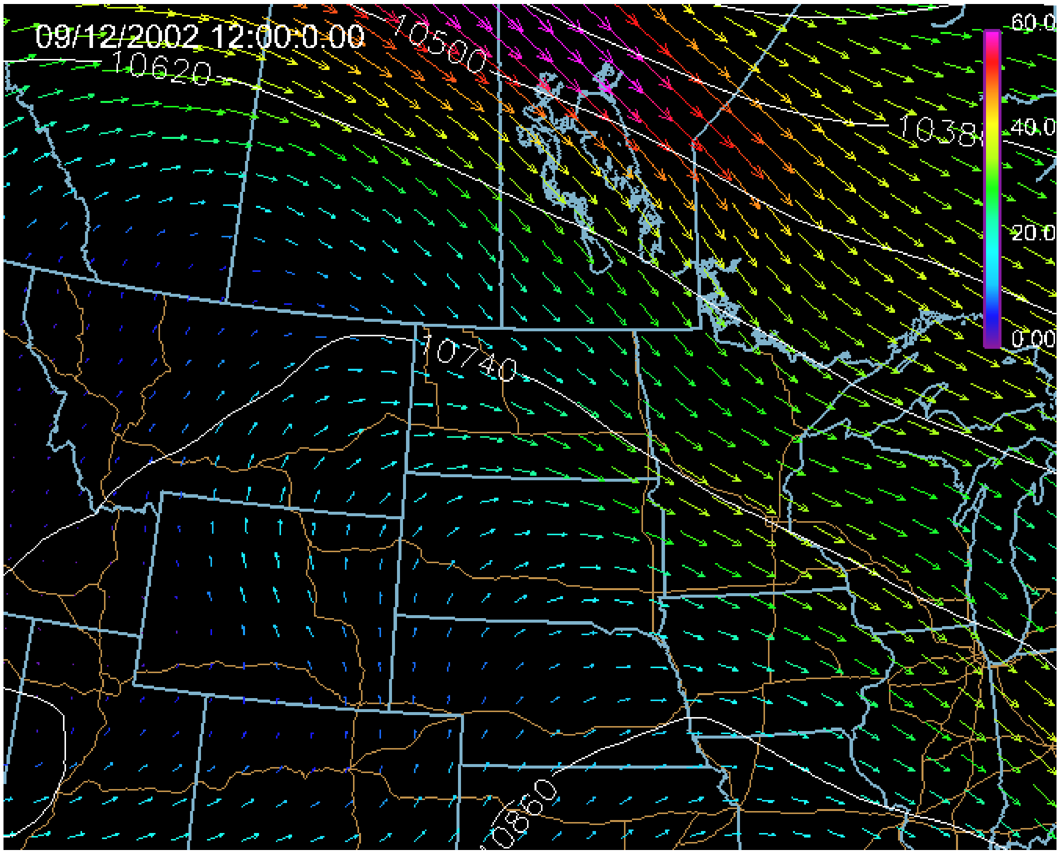

Figure 8. Geopotential height (m) and vector winds at 250 mb at 12 UTC on 12 September 2002.

Evaluation Period S1: 10 February – 18 February 2000

Three easterly wind events were identified within this evaluation period. Although the specified period of interest started on 10 February, an easterly wind episode was already underway on 9 February. In fact, the longest duration and most noteworthy of these three events occurred between 08 UTC on 9 February and 05 UTC on 10 February. As shown in Figure 9, this easterly wind event is typified by strong southwest-northeast surface pressure gradient created by a marked high pressure system (1026 mb) to the northeast in southern Manitoba and a northwest-southeast oriented trough of low pressure to the southwest of the central and western North Dakota region. This orientation of the pressure gradient along with the frictionally induced cross-isobaric and isallobaric flow results in a significant easterly wind episode. The slow propagation of the relevant systems coupled with the marked surface pressure gradient made this event one of the more noteworthy events.

The surface pressure system distribution can be explained by the upper-level dynamics associated with a major jet streak aligned along the United States – Canadian border running from North Dakota through the Great Lakes as can be seen at the 250 mb level in Figure 9. Upper-level convergence in the left entrance region of this jet streak over southern Saskatchewan and Manitoba is responsible, along with winter season radiative cold air mass formation, for the strong high pressure system seen in Figure 9. The low pressure trough is aligned with the right entrance region of this jet streak which is associated with divergence aloft and a reduction in surface pressure. Lee-side troughing from westerly flow in the lower mid-troposphere

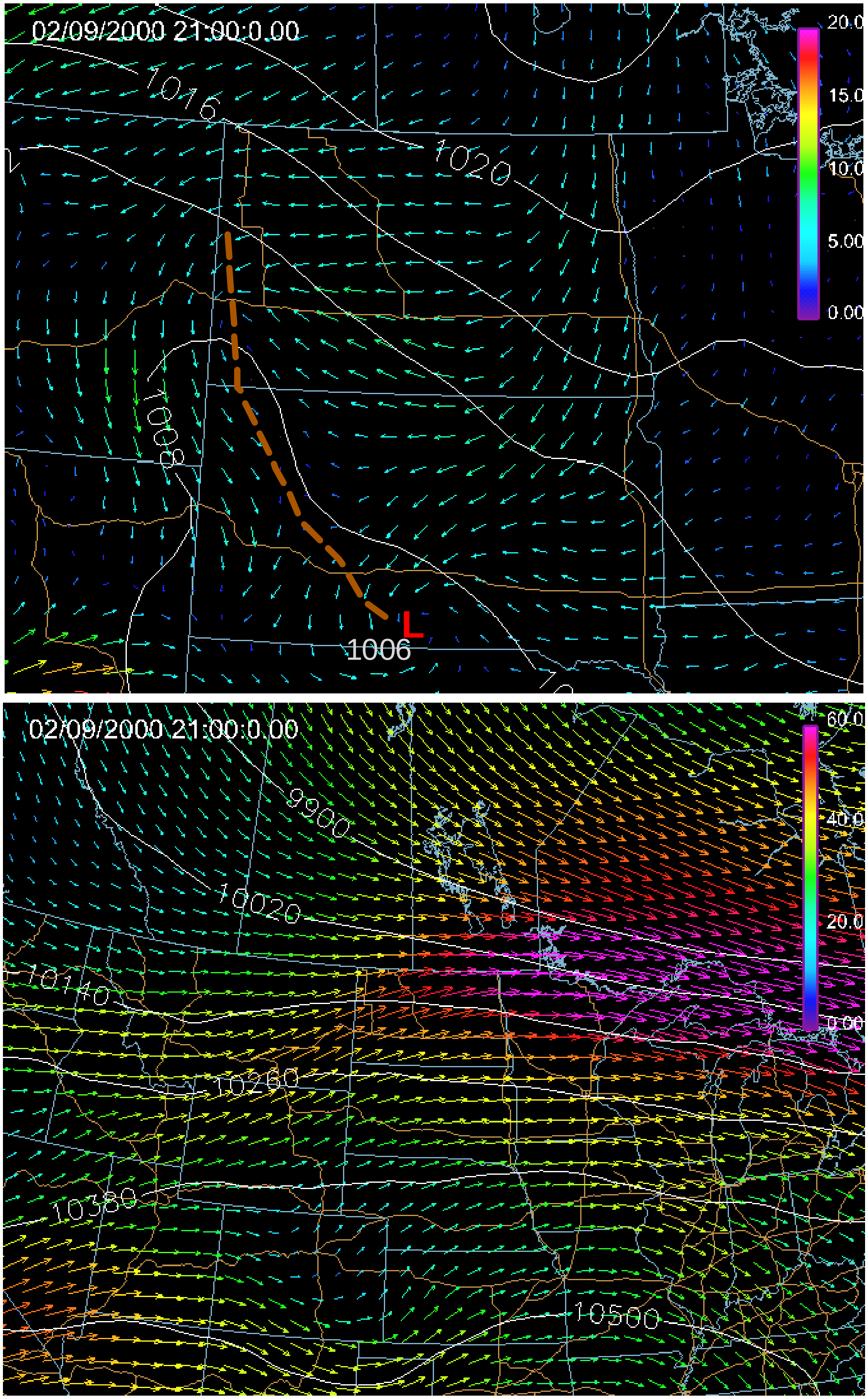

Figure 9. Surface pressure (mb) and vector winds at 21 UTC on 9 February 2000 top panel and geopotential height (m) and vector winds at 250 mb bottom panel. Color bar shows wind magnitude in m s^{-1}.

(~700 mb) may also be responsible, in part, for the trough of low pressure. A similar surface and upper-level atmospheric scenario was associated with the second easterly wind episode within the evaluation period S1 between 03 UTC and 17 UTC on 13 February. Aside from the displacement of the surface trough farther to the southwest, the orientation of the surface pressure gradient and the location and dynamical reasoning for the high pressure system are the same. Lee side trough production results from increasing westerly flow over the central Front Range of the Rocky Mountains. The third episode within S1 was a more minor event occurring between 01 UTC and 10 UTC on 15 February. In this scenario, an initial low pressure system developing in southeast Montana was supplanted in regional influence by a more intense low pressure system from cyclogenesis in southern South Dakota. This evolution of surface pressure systems rapidly backed the winds to a more northerly direction.

Evaluation Period S2: 11 December – 24 December 2000

No significant easterly wind events were found for this period. There were two minor southeasterly wind episodes during the time between 10 UTC and 18 UTC on 12 December and between 11 UTC and 22 UTC on 15 December. However, the assumed trajectory of parcels, especially when considering the veered nearly south winds at 900 mb did not appear conducive for significant westerly transport. In both of these cases, the trajectory of the cyclone responsible for the wind episodes passed too far north for optimal exposure to the easterly wind region of the system.

Evaluation Period S3: 7 February – 19 February 2001

One significant easterly wind event was present during the period that occurred between 10 UTC on February 10 and 01 UTC on 12 February. More specifically, this event featured winds predominantly from the east-southeast. The large-scale forcing for this wind regime was very similar to event S1, with strong high pressure (1036 mb) to the northeast in southern Manitoba and a trough of low pressure situated downstream in the lee of the Rockies from southeast Montana to western Nebraska as shown in Figure 10. Similar to event S1, a southwest-northeast pressure gradient was established (not quite as optimally configured as S1), that induced marked east-southeasterly winds across central and western North Dakota. The 10 m winds were typically in the 6-8 m s^{-1} range in the heart of this event over much of central and western North Dakota. As in several of the events described previously, this lee-side trough was associated with southwest flow in the lower mid-troposphere (~700 mb) passing over the central Rockies. The high pressure region appears to be associated with a convergent confluence region in the upper troposphere in the region over and near southern Manitoba. Additionally, anticyclogenesis is also likely due to winter season radiative cold air mass formation.

Evaluation Period S4: 14 March – 24 March 2002

Four episodes of significant easterly winds occurred during this evaluation period. The most impressive of these, and one of the most notable of any of the events analyzed for this study, occurred between 08 UTC on 24 March and 09 UTC on 25 March. The large-scale forcing for this event is dominated by a very large and intense (1038 mb) high pressure system located in southern Manitoba as seen in Figure 11. This anticyclone has established a marked southwest-northeast pressure gradient over North Dakota that has set up the low-level forcing that supports the 5-7 m s^{-1} easterly winds common over much of North Dakota. More striking still, the 900 mb vector winds shown in Figure 11 reveal strong easterlies in the 10-13 m s^{-1} range over much of the western half of North Dakota. Unlike many of the events analyzed, lee-side troughing has less to do with this easterly wind episode than the location, orientation and slow movement of the dominant high pressure system. The high pressure system may be dynamically explained by noting the locational association between the left entrance region of a bifurcated jet streak over southeast Manitoba and the location of the surface anticyclone as seen in Figure 12. The upper-level convergence in this jet stream quadrant in conjunction with late winter season radiative cold air mass formation are key factors in the formation of this high pressure system.

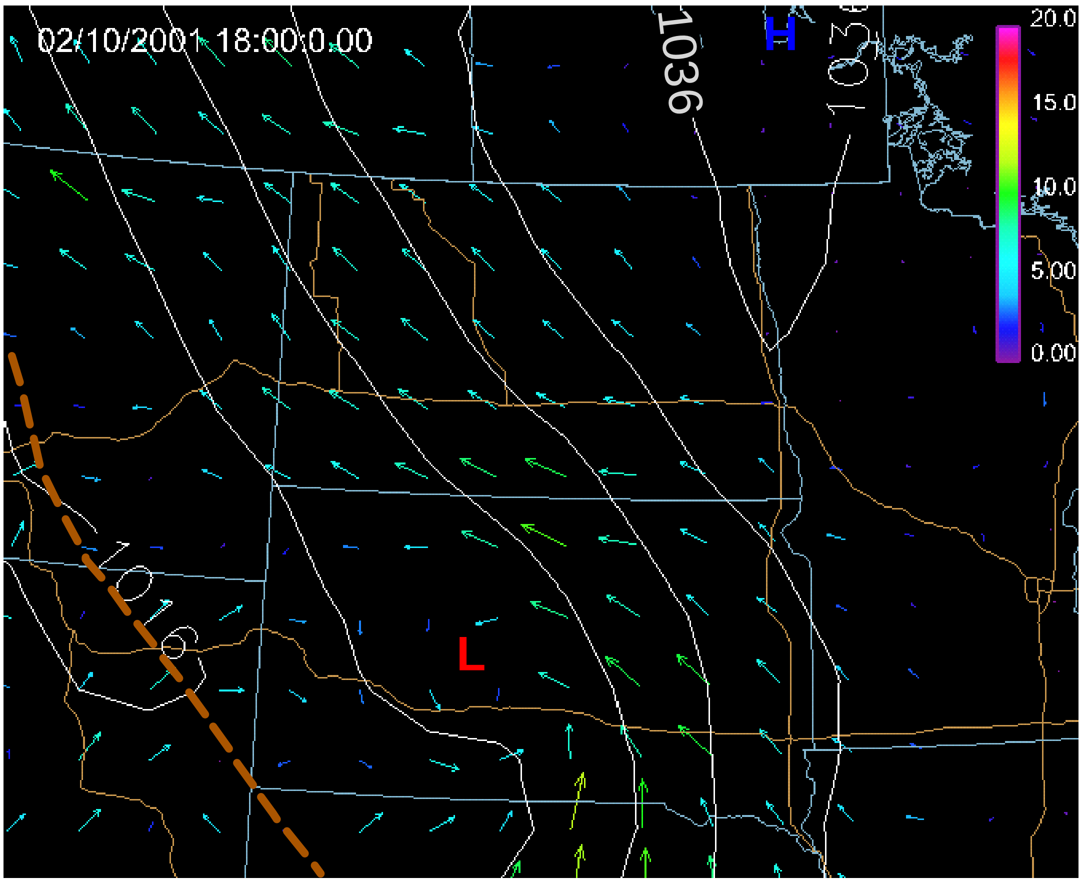

Figure 10. Surface pressure (mb) and vector winds at 18 UTC on 10 February 2001. Color bar shows wind magnitude in m s^{-1}.

Other east wind episodes within the S4 period include the weak east wind event occurring between 12 UTC on 14 March and 03 UTC on 15 March. In this case, a nearly stationary high pressure system (1022 mb) centered over southern Manitoba in conjunction with generally lower pressure to the south from a large cyclone moving northeast out of eastern Colorado created a modest southwest-northeast pressure gradient that supported weak easterly low-level winds. This event terminated when surface pressures rose over the Plains states south of North Dakota (eliminating the pressure gradient) in the wake of the cyclone moving into the upper Midwest.

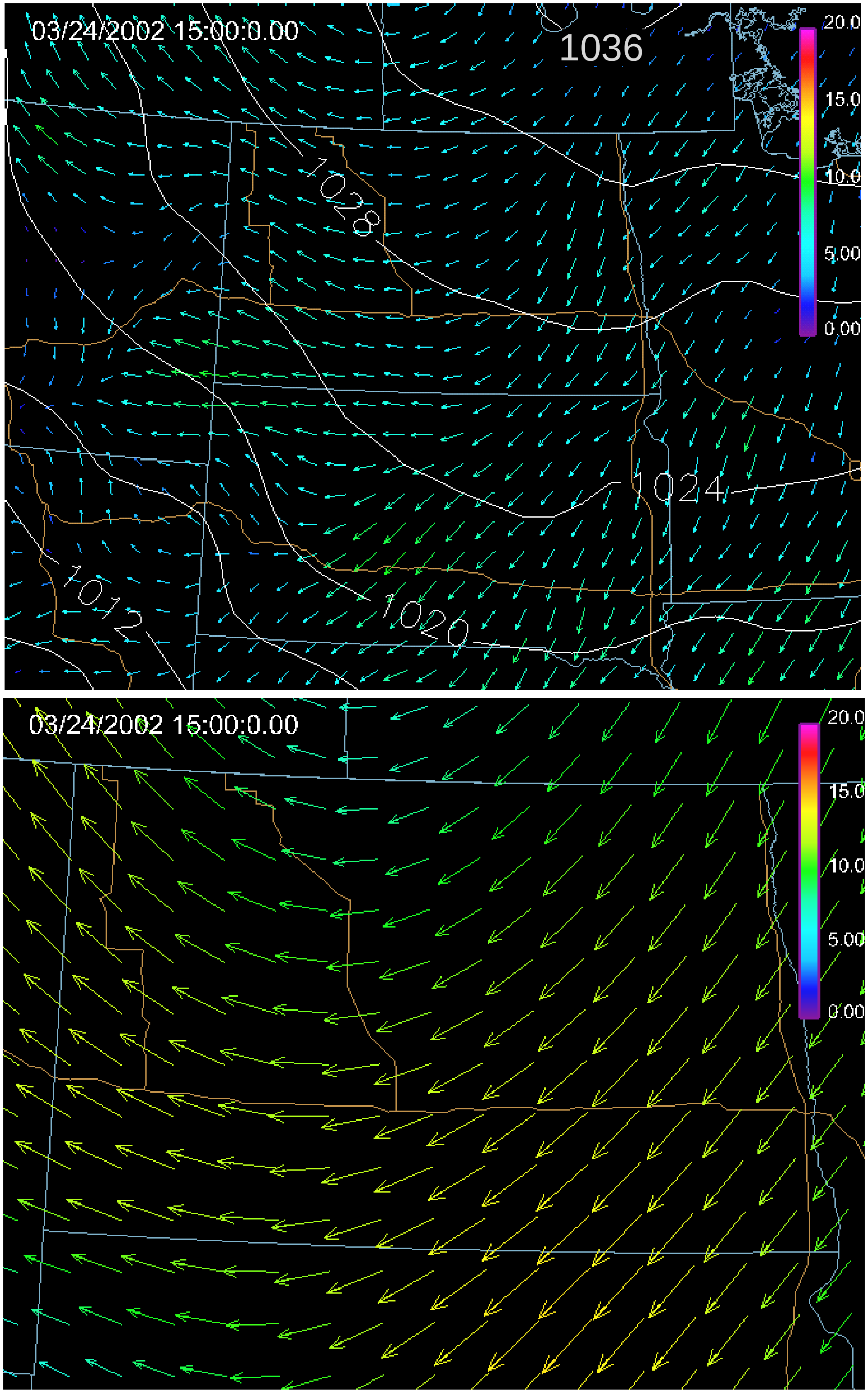

Figure 11. As in Figure 1 except at 15 UTC on 24 March 2002.

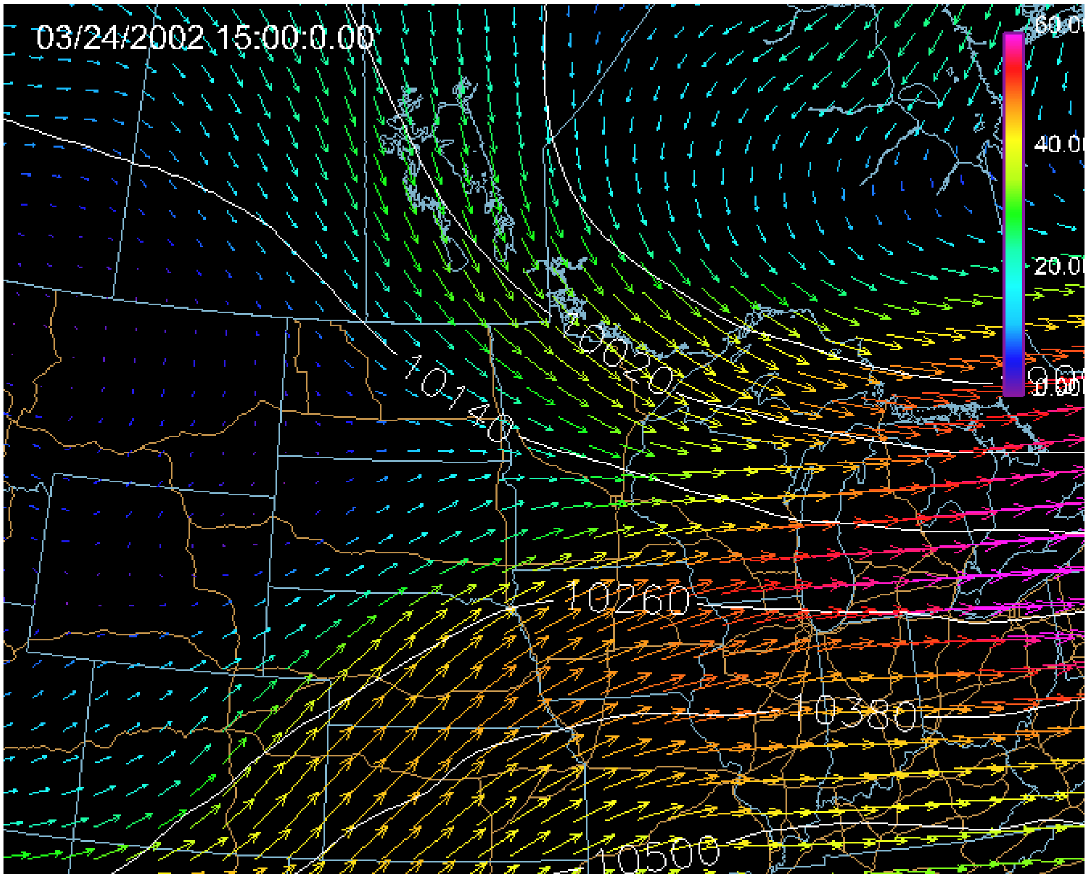

Figure 12. Geopotential height (m) and vector winds at 250 mb at 15 UTC on 24 March 2002.

The next easterly wind event occurred between 11 UTC and 20 UTC on 16 March. In this episode, easterly flow developed in the favorable pressure gradient north of a warm front associated with a low moving into North Dakota from Montana. Given the non-optimal west to east path of the cyclone through northern North Dakota, this event was of short duration. As the warm front moved northward through western and central North Dakota, the east winds rapidly turned southerly at locations south of the warm front, terminating the episode of easterly low-level flow.

The final noteworthy easterly wind episode within S4 occurred between 12 UTC on 19 March and 04 UTC on 20 March. In this case, an easterly flow regime is present north of a warm front associated with cyclogenesis in southeast Montana and northeast Wyoming. The position of the surface warm front lying just north of the North Dakota – South Dakota border was ideal for an extended period of easterlies over central and western North Dakota. At 900 mb in the heart of this event, easterly flow in the 5-8 m s^{-1} range was common over much of western and central North Dakota. This event terminated as the cyclone moved eastward through central South Dakota.

5. Summary

To produce a low-level easterly wind episode of considerable duration over central and western North Dakota, a south-north or southwest-northeast oriented pressure gradient must be established. In the numerous cases examined herein, three synoptic scenarios were observed to establish the requisite low-level pressure gradient. The most common scenario involved a low pressure trough and/or cyclone development in the lee of the central Rocky Mountains of Colorado and Wyoming to the southwest of North Dakota. In conjunction with this low pressure region to the southwest, a marked high pressure system to the northeast was present to establish the required low-level pressure gradient across central and western North Dakota for easterly low-level winds. The second most common synoptic scenario involved cyclogenesis southwest or west of North Dakota with the cyclone ultimately passing just south of central and western North Dakota (optimally near the border with South Dakota). This cyclone trajectory was ideal for maximizing the easterly wind duration for regions north of the warm front (i.e. the area of interest for this study). The final synoptic scenario for extend easterlies involved the presence of a slow moving large and intense high pressure system to the northeast, usually centered in or near southern Manitoba. Although in the minority of the easterly wind scenarios identified, one of the most impressive easterly wind events analyzed (the first event in evaluation period S1) involved this slow-moving intense anticyclone scenario.

In general, the broad synoptic pressure system configurations noted in these specific events should not be considered unusual, especially in the winter and transition seasons. The incidence of lee-side troughing east of the central Rockies of Colorado and Wyoming occurs frequently in conjunction with a marked westerly or southwesterly component to the upper-level flow that accompanies the positioning of the jet stream over this region. Additionally, cyclogenesis is favored within this region of lee-troughing in association with jet streaks moving along the axis of the jet stream. Further, anticyclones developing and moving southeastward across the southern Canadian provinces of Saskatchewan and Manitoba occur regularly in these winter and transition seasons.

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Dr. Lee is a senior atmospheric scientist with expertise in numerical modeling, mesoscale meteorology and severe convective storms. He received a Ph.D. in Atmospheric Sciences from the University of Illinois in 1995 where he investigated tornado genesis processes and thunderstorm outflow dynamics. This work continued in post-doctoral appointments at the University of Illinois and at the National Center for Supercomputing Applications. As a tenured Associate Professor at the University of Northern Colorado, Dr. Lee's research included investigations of severe thunderstorm outflow dynamics, supercell thunderstorm morphology, tornado genesis, and thunderstorm initiation. He was the project director of the spring 2003 tornadic thunderstorm field program called Project ANSWERS 2003 (Analysis of the Near-Surface Wind and Environment Along the Rear Flank of Supercells). Prior to his graduate work, Dr. Lee was employed as a Performance Engineer in the Flight Operations Division with Northwest Airlines. He is a member of the American Meteorological Society and the National Weather Association and has authored or co-authored over two dozen scientific journal articles and conference papers.

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